J. Geomag. Geoelectr., **30**, 511–522, 1978

Local Magnetic Field Variations and Stress Changes Near a Slip Discontinuity on the San Andreas Fault

M.J.S. JOHNSTON

U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, U.S.A.

(Received November 25, 1977)

Data from an array of proton magnetometers in central California indicate that a systematic decrease in magnetic field of about 2γ in 5 years has occurred in a localized region near Anzar, California, just north of the creeping section of the San Andreas fault. This field change has most likely resulted from changes in crustal stress in this region, although an unknown second-order effect of secular variation cannot be excluded as a alternate explanation. Tectonomagnetic models have been developed using dislocation modeling of slip on a finite section of fault. Assuming a fault geometry and rock magnetization, these models relate changes in stress, fault slip, and fault geometry to surface magnetic field anomalies. A large-scale anomaly, opposite in sense to that observed but of similar amplitude, would be expected to have accumulated in this area during the past 70 years. A localized 5-bar decrease in shear strain on the fault resulting from about 2 cm of slip on a 0.25-km square patch at a depth of 1 km beneath the surface trace of the fault opposite the magnetometer could explain the observed data and still be compatible with the geodetic strain measurements in the area. Other models of limited local slip are equally possible. The occurrence of a moderate magnitude earthquake in this region will allow comparison of stress changes estimated by different techniques.

1. Introduction

The magnitude of crustal stress changes accompanying faulting is uncertain. On one hand direct laboratory measurements (STESKY and BRACE, 1973) and deep mine fracture experiments in intact rock (SPOTTISWOOD and MCGARR, 1975) indicate that the shear stress at about 10 km is 1 to 2 kbars and that stress changes of up to 1 kbar should therefore accompany faulting. On the other hand an upper limit on the average shear stress on the fault of a few hundred bars is indicated by the absence of a detectable heat flow anomaly near the San Andreas fault (BRUNE *et al.*, 1969; LACHENBRUCH and SASS, 1973). The mean displacement-to-length ratios for earthquakes that rupture the surface also indicate an average change in stress of about 100 bars (CHINNERY and PETRAK, 1968). Furthermore, BRUNE (1970) and others have argued from theoretical seismic source models for seismic shear stress changes (stress drops) that are typically less than 100 bars. Comminution and chemical changes probably also contribute to minor changes in stress levels on active faults but are not sufficient to explain this challenging paradox.

Independent estimates of changes in stress distribution around active faults are possible as a consequence of the stress sensitivity of the magnetization of crustal rocks (STACEY, 1964). These estimates are generally poorly constrained since the distribution of magnetization and its stress sensitivity are poorly known. Within these uncertainties, however, meaningful order-of-magnitude stress estimates can be determined. These can be related to the paradox discussed above. This paper primarily concerns the use of a tectonomagnetic model to attempt a stress estimate at the location of a particular slip discontinuity on the San Andreas fault where a change in local magnetic field has been observed.

2. Local Magnetic Anomalies

The history of high-quality magnetic measurements along active faults in California is extremely short (JOHNSTON *et al.*, 1976). It is interesting, but possibly coincidental, that even with this short history, the regions where significant local anomalies have been reported are at or near the ends of the recent major ruptures ($M>8$) within the fault system. These earthquakes are shown in Fig. 1, together with all earthquakes $M \geqq 5$ since 1900 and the amplitude and error estimates of the

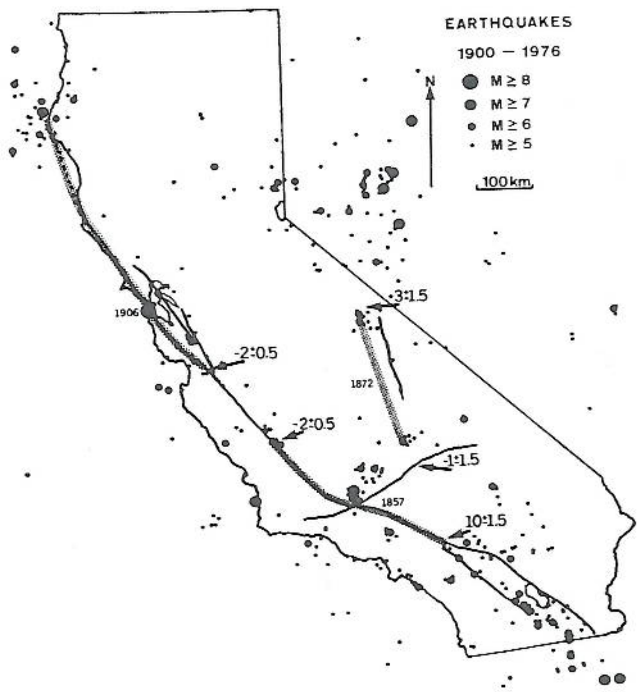


Fig. 1. Major recent fault ruptures (cross-hatched) for earthquakes $M>8$ and the locations of earthquakes with $M \geqq 5$ (dots) in California and western Nevada since 1900 from TOPPOZADA *et al.* (1976), BOLT and MILLER (1975), HILEMAN *et al.* (1973), and FRIEDMAN *et al.* (1976). Included also are the amplitude and error estimates of magnetic anomalies that have occurred since 1973.

magnetic anomalies that have occurred since 1973. Details of most of the magnetic data can be found in JOHNSTON *et al.* (1976), WILLIAMS and JOHNSTON (1976), and SMITH and JOHNSTON (1976).

The data that form the subject of this study have been recorded just north of San Juan Bautista at the south end of the 1906 earthquake rupture. The locations of continuously recording magnetometers in this region are shown in Fig. 2. All magnetometers are synchronized. The sensitivity and stability of each is 0.25γ and the sampling rate is once per minute (SMITH and JOHNSTON, 1976). The data from each adjacent station are differenced to isolate changes of local origin and to reduce effects of ionospheric and magnetospheric origin.

The magnetizations of the rocks in this area can exceed 10^{-3} emu (in some places 10^{-2} emu) and thus provide a sensitive stress transducer in this region. Similar clustering of rocks with high magnetizations occurs also at the ends of the 1857 earthquake ($M>8$) rupture in southern California and the 1872 earthquake ($M>8$) rupture in Owens Valley.

Space-time plots for the period 1974 to 1976 of differential magnetic fields across the region from where the fault is locked to where the fault is slipping are shown in

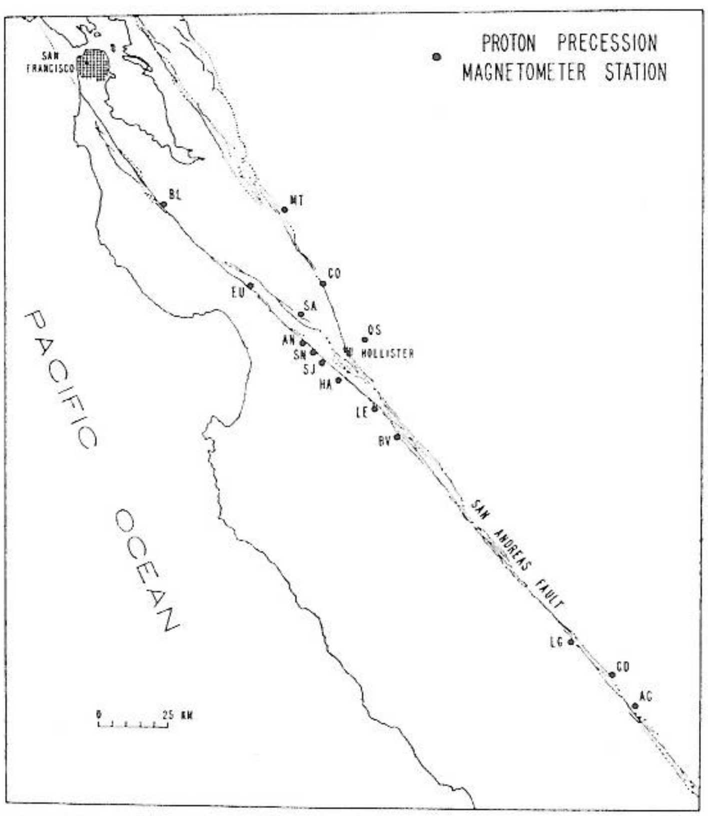


Fig. 2. Locations of continuously recording magnetometers in central California presently telemetered to Menlo Park just south of San Francisco.

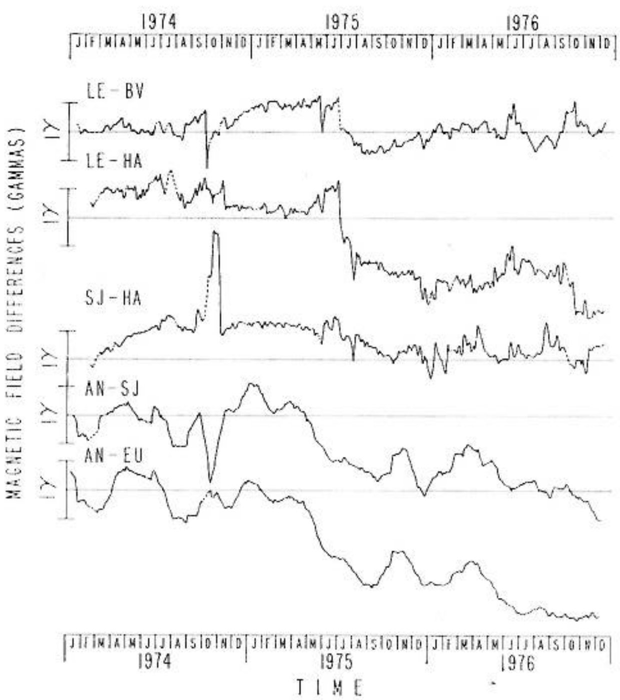


Fig. 3. Space-time history plots of magnetic field differences from station pairs to the southeast and the northwest along the fault from the point where aseismic slip ceases.

Fig. 3. A systematic decrease with time of the difference AN–EU and AN–SJ is clearly evident. The total change over the 3-year period, due primarily to a decreasing field at station AN, is about 2.5 γ. Independent data from repeated magnetic surveys between different sites near AN indicate a similar result (JOHNSTON *et al.*, 1976).

There appear to be two possible explanations for these data. An obvious candidate is the secular variation of the geomagnetic field. In this case, however, direct effects of secular variation can be ruled out since (1) the apparent wavelength necessary would be a few tens of kilometers and (2) the change in the difference AN–SJ is opposite in sense to that expected for the present secular variation of about -30 γ/year. This arises since the net change in field at AN for large-wavelength, long-period geomagnetic field fluctuations is less than at other stations. The difference AN–SJ should increase for a 30-γ field decrease over 12 months in about the same way that it does during the 50-γ field decrease that occurs each day. For much the same reasons indirect or second-order effects of secular variation seem unlikely but cannot be ruled out.

A second possibility is a stress-induced magnetic change. This should be expected in this area if any substantial stress variation occurs. There are clearly insufficient data to attempt any rigorous inversion of the magnetic data to obtain the likely change in stress. The problem reduces therefore to finding the simplest model and inferred stress that will explain the data. This is treated in the next section.

3. Tectonomagnetic Model

Following CHINNERY (1963), PRESS (1965), and ROSENMAN and SINGH (1973), the stress distribution around a finite dislocation on a vertical fault can be calculated. These models relate the slip geometry and distribution to stresses and strains in the surrounding material. The details of the geometry and coordinate system are shown in Fig. 4. The fault has a length L. The top is at a depth d and the bottom is at a depth D. This type of model, and generalizations from it to variable slip and variable geometry (McHUGH and JOHNSTON, 1978), have been used to calculate tilt, stresses, and strains for various slip geometries on the San Andreas fault.

In particular, models have been fit to (1) the general region near San Juan Bautista, where a transition from about 10% to less than 0.1% of the average plate displacement rate given in ATWATER and MOLNAR (1973) occurs in the surface fault-displacement measurements and (2) the general region on either side of the Cajon Pass end of the 1857 break where, historically, gradients in surface displacements have apparently occurred (SIEH, 1976). Only the simplest of these models, which can be applied to either of these two regions, is discussed here and is shown for the northern region in Fig. 5a.

In this model, the slip U is initially uniform and extends from San Juan Bautista to the southeast over the whole fault for at least 100 km. To the northwest, slip occurs only at depths below 11 km. Contours of maximum stress change (isopachs) derived from the sum of the principal stresses and normalized to $0.1U$, are plotted

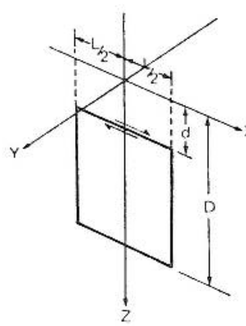
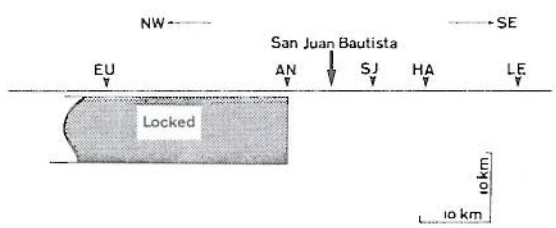


Fig. 4. Geometry and coordinate system used to model a vertical rectangular strike-slip fault.



San Andreas Cross-section

Fig. 5a. Simplified fault model near San Juan Bautista.

in Fig. 5b. The locations of recording magnetometers are shown as black dots. A slip of 100 cm gives shear-stress changes in the region around the end of as much as 20 bars. Quasistatic behavior can also be modeled but is not attempted here. For such a case, the slip boundary propagates along the fault together with the stress contour pattern, and a point on the surface would experience a transient stress field.

Following STACEY (1964), SHAMSI and STACEY (1969), and TALWANI and KOVACH (1972), the modification ΔI of the total magnetization $I(xyz)$ of a volume element of rock dv resulting from the imposition of a stress $\boldsymbol{\sigma}$ is found by first determining the components of magnetization in the direction of the principal stresses σ_1 from Eq. (1)

$$I_i = (D_{ji}) \begin{pmatrix} I_x \\ I_y \\ I_z \end{pmatrix} \tag{1}$$

where D_{ij} is the direction cosine matrix with $j = x, y, z$ for $i = 1, 2, 3$. Using the theoretically determined (STACEY and JOHNSTON, 1972) and experimentally supported (OHNAKA and KINOSHITA, 1968a, b) relation between change in magnetization ΔI_i in the σ_i direction, the values of ΔI_i can be found from:

$$\Delta I_i = \frac{C}{2} I_i(\sigma_j + \sigma_k - 2\sigma_i) \quad i, j, k = 1, 2, 3 \quad (i \neq j \neq k) \tag{2}$$

where C is the stress sensitivity ($\sim 10^{-4}\,\mathrm{bar}^{-1}$; STACEY and JOHNSTON, 1972) and $i, j, k = 1, 2, 3$, but $i \neq j \neq k$. The components ΔI_x, ΔI_y and ΔI_z in the x, y, z frame are then given by:

$$\begin{pmatrix} \Delta I_x \\ \Delta I_y \\ \Delta I_z \end{pmatrix} = (\Delta I_1, \Delta I_2, \Delta I_3)(D_{ji}) \tag{3}$$

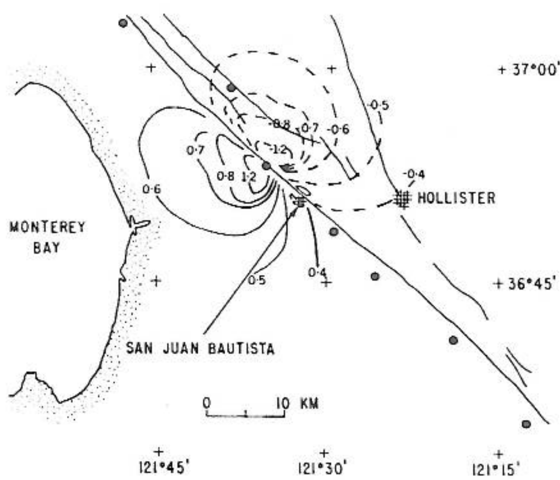


Fig. 5b. Contours of maximum stress ($\sigma_1 + \sigma_2$) in bars at the northern end of the aseismically slipping section of the San Andreas fault normalized by $0.1U$ where U is the total fault slip in centimeters.

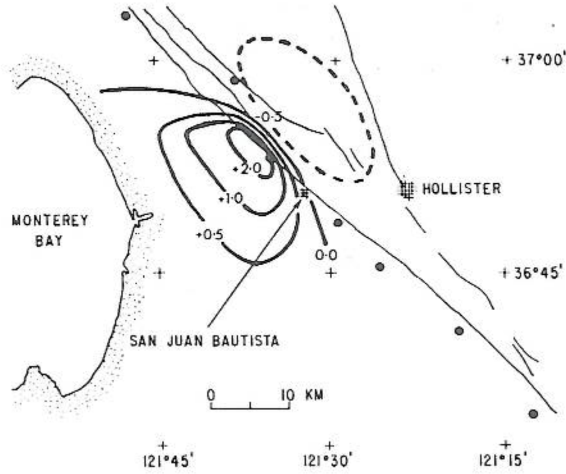


Fig. 5c. Contours of anomalous local magnetic field (γ) produced at the northern end of the slipping section of the San Andreas fault, if the region is assumed to have a magnetization of 10^{-3} emu.

and the surface magnetic anomaly components $\Delta F_{x,y,z}$ at a point $(x', y', 0)$ are determined (HILDERBRAND, 1975) by:

$$\Delta F_{x,y,z} = \int_v (\Delta \boldsymbol{I} \cdot \boldsymbol{\nabla}) \frac{d}{dx,\, y,\, z} \left(\frac{1}{r} \right) dv \tag{4}$$

where $r^2 = (x-x')^2 + (y-y')^2 + z^2$. The surface total field anomaly can then be determined from these components.

The model in Fig. 5a can thus be used to determine the surface total field anomaly contours that presumably have been accumulating since at least the time of the 1906 earthquake. A slip of 3 cm/year for the last 70 years from a depth of 1 km to a depth of 11 km to the southeast of San Juan Bautista and below 11 km to the northwest produces the surface anomaly pattern shown in Fig. 5c. The contour interval is in 1-γ unit if the average magnetization is 10^{-3} emu and 10 γ if the average magnetization is 10^{-2} emu. The measured magnetizations of the surface rocks are typically about 10^{-3} emu but can exceed 10^{-2} emu in the installation region of station AN. If the remanent component is assumed to be oriented parallel to the induced component, the static magnetic anomaly indicated by the aeromagnetic map of the area (HANNA *et al.*, 1972) could be explained by stacked slabs of material with magnetizations generally increasing with depth from 10^{-4} emu to 10^{-3} emu except for a highly magnetized slab ($I_t \sim 10^{-3}$) about 5-km long, 3-km wide, and 5-km deep around station AN. The effects of introducing a more complex magnetization distribution complicates the surface anomaly pattern but not the general amplitudes indicated by the tectonomagnetic calculations.

5. Conclusions

The systematic decrease in local magnetic field at present occurring near San Juan Bautista on the San Andreas fault constitutes one of the most significant well-recorded field perturbations yet obtained along the fault. It is in this region that the 1906 rupture stopped, and a transition occurs from a stable sliding fault to the southeast to a locked and generally aseismic fault to the northwest.

Determination of the physical origin of the observed change is hindered by the paucity of data. An accumulated field change of about 2γ would be expected throughout this general region if the presently observed rate of strain accumulation is assumed to have been uniform for the past 70 years since the 1906 earthquake. However, the observed change is occurring too rapidly to be due to the average accumulation of strain, and more significantly, has an opposite sign. Furthermore, the absence of any abnormal large-scale strains in the geodetic data in this area (PRESCOTT and SAVAGE, 1978) limits the amount of aseismic slip during the observational period. The simplest class of models that explain the data invokes localized and quite near-surface systematic encroachment of slip into the locked section of the fault. Other possibilities such as a growing but localized stress concentration or heterogeneity could be suggested but cannot presently be independently supported. Regardless of whether fault slip or a local stress concentration is occurring, at least 5-bars change in stress is required to explain the magnetic data if the source is within a few kilometers of the earth's surface.

It is fortunate, both for determining the reality of a mechanical origin for the magnetic observations and for quantifying the models suggested, that a number of new magnetometers and other types of instruments (strain, tilt) are now installed in the region just north of San Juan Bautista. Should a moderate magnitude earthquake occur, for the first time, changes in stress estimated by different techniques can be compared.

I thank Bruce Smith for providing, unpublished data, Dr. Leroy Allredge for an unpublished preprint, and Allan Lindh for an unpublished integration of California seismic data and stimulating discussion.

REFERENCES

ATWATER, T. and P. MOLNAR, Relative motion on the Pacific and North American plates deduced from sea floor spreading in the Atlantic, Indian and South Pacific oceans, in *Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System*, edited by R.L. Kovach and A. Nur, pp. 136–148, School of Earth Sciences, Stanford University, Stanford, California, 1973.

BOLT, B.A. and R.D. MILLER, Catalogue of earthquakes in northern California and adjoining Areas—January 1910–13 December 1972, Bulletin of the Seismographic Stations, University of California, Berkeley, 568 pp., 1975.

BRUNE, J.N., Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, **75**, 4997–5009, 1970.

BRUNE, J.N., T.L. HENYEY, and R.F. ROY, Heat for, stress, and rate of slip along the San Andreas fault, California, *J. Geophys. Res.*, **74**, 3821–3828, 1969.

CHINNERY, M.A., The stress changes that accompany strike-slip faulting, *Bull. Seismol. Soc. Am.*, **53**, 921–932, 1963.

CHINNERY, M.A. and J.A. PETRAK, The dislocation model with variable discontinuity, *Tectonophysics*, **5**, 513–529, 1968.

FRIEDMAN, M.E., J.H. WHITCOMB, C.R. ALLEN, and J.A. HILEMAN, Seismicity of the Southern California Region, 1 January 1972 to 31 December 1974, Seismological Laboratory, California Institute of Technology, Pasadena, California, 81 pp., 1976.

HANNA, W.F., R.D. BROWN, D.C. ROSS, and A. GRISCOM, Aeromagnetic reconnaissance along the San Andreas fault between San Francisco and San Bernardino, California: U.S. Geological Survey, Geophys. Inv. Map GP 815, scale 1:250,000, 1972.

HILDERBRAND, T., Seismomagnetism, Ph.D. thesis, University of California, Berkeley, 1975.

HILEMAN, J.A., C.R. ALLEN, and J.M. NORDQUIST, Seismicity of the southern California region 1 January 1932 to 31 December 1972, Seismological Laboratory, California Institute of Technology, Pasadena, 404 pp., 1973.

JOHNSTON, M.J.S., B.E. SMITH, and R. MUELLER, Tectonic experiments and observations in western U.S.A., *J. Geomag. Geoelectr.*, **28**, 85–97, 1976.

LACHENBRUCH, A.H. and J.H. SASS, Thermo-mechanical aspects of the San Andreas fault, in *Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System*, edited by R.L. Kovach and A. Nur, pp. 192–205, School of Earth Sciences, Stanford University, Stanford, California, 1973.

MCHUGH, S. and M.J.S. JOHNSTON, Dislocation modelling of creep related tilt changes, *Bull. Seismol. Soc. Am.*, **68**, 155–168, 1978.

OHNAKA, M. and H. KINOSHITA, Effect of uniaxial compression on Remanent Magnetization, *J. Geomag. Geoelectr.*, **20**, 93, 1968a.

OHNAKA, M. and H. KINOSHITA, Effect of axial stress upon initial susceptibility of an assemblage of fine grains of Fe_2TiO_4–Fe_3O_4 solid solution series, *J. Geomag. Geoelectr.*, **20**, 107, 1968b.

PRESCOTT, W. and J.C. SAVAGE, Strain accumulation rates in the western United States between 1970 and 1976, *J. Geophys. Res.*, 1978 (in press).

PRESS, F., Displacements, strains and tilts at teleseismic distances, *J. Geophys. Res.*, **70**, 2395–2412, 1965.

ROSENMAN, M. and S.J. SINGH, Quasi-static strains and tilts due to faulting in a viscoelastic halfspace, *Bull. Seismol. Soc. Am.*, **63**, 1737–1742, 1973.

SHAMSI, S. and F.D. STACEY, Dislocation models and seismomagnetic calculations for California 1906 and Alaska 1964 earthquakes, *Bull. Seismol. Soc. Am.*, **59**, 1435–1448, 1969.

SIEH, K., Pre-historic large earthquakes on the San Andreas fault in the area of the Palmdale Uplift, *EOS, Trans. Am. Geophys. Union*, **57**, 899, 1976.

SMITH, B.E. and M.J.S. JOHNSTON, A tectonomagnetic effect observed before a magnitude 5.2 earthquake near Hollister, California, *J. Geophys. Res.*, **81**, 3556–3560, 1976.

SPOTTISWOOD, S.M. and A. MCGARR, Source parameter of tremors in a deep-level gold mine, *Bull. Seismol. Soc. Am.*, **65**, 93–112, 1975.

STACEY, F.D., The seismomagnetic effect, *Pure Appl. Geophys.*, **58**, 5–22, 1964.

STACEY, F.D. and M.J.S. JOHNSTON, Theory of the piezomagnetic effect in titanomagnetite bearing rocks, *Pure Appl. Geophys.*, **97**, 146–155, 1972.

STESKY, R.M. and W.F. BRACE, Estimation of frictional stress on the San Andreas fault from laboratory measurements, in *Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System*, edited by R.L. Kovach and A. Nur, pp. 206–213, Stanford University Publications, 1973.

TALWANI, P. and R.L. KOVACH, Geomagnetic observations and fault creep in California, *Tectonophysics*, **14**, 245–256, 1972.

TOPPAZADA, T.R., D.L. PARKE, and C.T. HIGGINS, Seismicity of California, 1900–1931, unpublished manuscript, 1976.

WESSON, R.L., R.O. BURFORD, and W.L. ELLSWORTH, Relationship between seismicity, fault creep and crustal loading along the central San Andreas fault, in *Proceedings of the Conference on Tectonic*

Problems of the San Andreas Fault System, edited by R.L. Kovach and A. Nur, pp. 303–321, School of Earth Sciences, Stanford University, Stanford, California, 1973.

WILLIAMS, F.J. and M.J.S. JOHNSTON, Differential magnetometer measurements on the Palmdale Bulge, and along the San Jacinto fault, *EOS, Trans. Am. Geophys. Union*, **57**, 898, 1976.